ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPA152

RESULTS OF THE ELLIPTICAL CRYOMODULE QUALIFICATION AT THE ESS TS2

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Abstract

The cryomodule qualification test stand (TS2) at Lund has been commissioned fully in 2021 and is delivering the components for the installation in the linac, which has started in March 2023 after the end of the cryogenic distribution system commissioning. All the available medium beta cryomodules have been tested and the facility is now delivering the high beta cryomodules for the full scope of the linac. Statistics of the tests and operational experience of the facility is reported here.

INTRODUCTION

At TS2 [1] each cryomodule (CM) goes through an extensive workflow for Site Acceptance Testing (SAT) before being considered Ready For Installation (RFI) in the linac tunnel [2, 3]. The workflow consists of different phases, each comprising the execution of test protocols and resulting in write-up of findings reports [4]. The ESS TS2 operation team takes advantage of long-term collaboration with IFJ PAN [5], acting together as a unified team. This experience allows to continuously improve the test procedures, optimise execution times and gain valuable operation experience for the superconducting linac operation.

We present a collection of qualitative and quantitative performance indicators related to the acceptance workflow and share a selection of operational results and limitations associated with acceptance criteria and facility uptime.

CM Test Plan Activities

The test plan for CM acceptance aims at maximising the CM testing throughput. In short, after reception each cryomodule follows an incoming inspection and is prepared for bunker installation. When the bunker becomes available the CM is then transferred into it and installation takes place (including interconnections of vacuum, cryogenics and radio-frequency distribution systems). Then the warm validation is started (mainly power coupler conditioning) followed by cool down and cold validation (where couplers and cavities are first conditioned, then driven to maximum performance in open and closed loop, and assessment of heat loads taken). The CM is then warmed up, followed by disconnections from the bunker. It can then be transported out of the bunker (after receiving authorization from the radioprotection service), allowing for the installation of the next CM. Final preparations for dispatch are completed and the CM is finally transported to the storage area.

A positive outcome of the SAT deems the CM at the RFI stage for the tunnel. The test phases of the CM SAT are shown in Fig. 1, with the layout of the test facility.

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Figure 1: Phases of the TS2 CM SAT.

RUN STATISTICS

The statistics of series modules is presented in the following paragraphs. A total of 7 medium beta (MB) and 8 high beta (HB) cryomodules have been delivered by CEA to ESS, out of the foreseen 9 MB and 21 HB needed for the full scope of the 5 MW ESS linac. At present a total of 10 elliptical cryomodules have gone through the SAT cycle: the MB prototype, all the 7 MB received and 2 HB. All the HB are being prepared for the testing phase.

Total Time in Bunker

The preparation phases before the test (incoming checks, cable terminations, coupler doorknob transition assembly, etc.) and the final provisions for installation (compressed water manifold, instrument splitboxes, etc.) are usually performed concurrently in the preparation area or in the temporary CM storage areas in the RF gallery.

To maintain the necessary throughput of the RFI preparation it is necessary to limit the time needed in the bunker of the TS2. Figure 2 shows the number of days in the bunker for all tested CM. The Prototype CM, which is shown in the left plot with the series, has been used to commission the cryogenic and test infrastructure and several cryogenic cycles were performed before the RF tests. The plot to the right shows the learning curve obtained after a few tests.

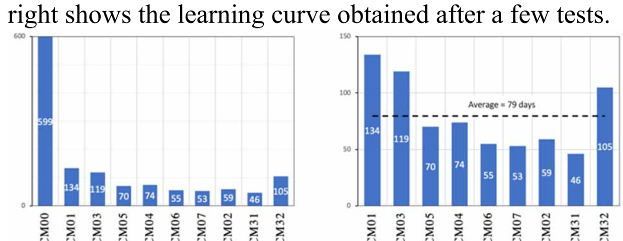

Figure 2: Number of days in bunker including prototype (left) and only for the series (right).

The test of the second HB was extended due to three trips of the cryoplant, requiring to warmup the infrastructure.

Power Coupler Conditioning Time

Non-resonant power coupler (PC) conditioning is performed at warm before the cooldown and at cold during the cryogenic stabilization, before cavity tuning to resonance. The power is swept with increasing pulse length and

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repetition rate from 1 Hz, 50 us to the nominal duty cycle of 14 Hz, 3.2 ms, in a predetermined sequence defined by CEA, using the cavity vacuum to drive the increase/decrease of RF. RF power is swept up to 1.2 MW for the lower duty cycles below 0.5 ms RF pulse length, and up to the nominal power of unloaded operation of 300/400 kW (MB/HB) for higher duty cycles. An automated EPICS sequence drives the LLRF system in open loop. Figure 3 shows the conditioning times of all tested CMs.

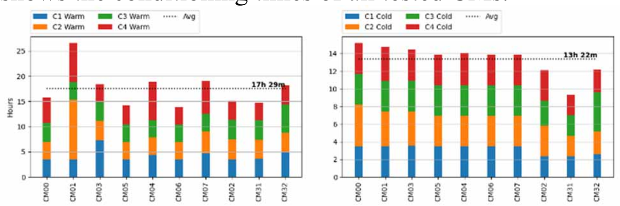

Figure 3: Warm (Left) and Cold (Right) conditioning.

Cavities Conditioning and Operation

After coupler conditioning and achieving full thermalization of all inner CM components and of the 2K bath, the cavities are tuned to resonance and possible multipacting levels are conditioned in open loop at the nominal duty cycle until either reaching limiting phenomena (Quench, Thermal Breakdown, High Field emission levels, Coupler arcing) or the administrative limit of 300/400 kW (MB/HB) for operation in full reflection with no beam.

After the cavity conditioning, piezo-assisted closed loop operation allows to determine the cavity performances.

CM PERFORMANCE STATISTICS

As part of the acceptance criteria for each CM we track the individual cavity performances and associated limitation mechanisms. Moreover, we measure the heat loads dissipated to the cryogenic system, by doing independent measurements of the heat load without RF power (static) and those generated from RF operation (dynamic) [6].

Cavities Performance

Capability of piezo-assisted closed loop became fully available after the testing of the first six modules. For the early modules a larger uncertainty due to the Lorenz Force Detuning (LFD) effect at high fields is present.

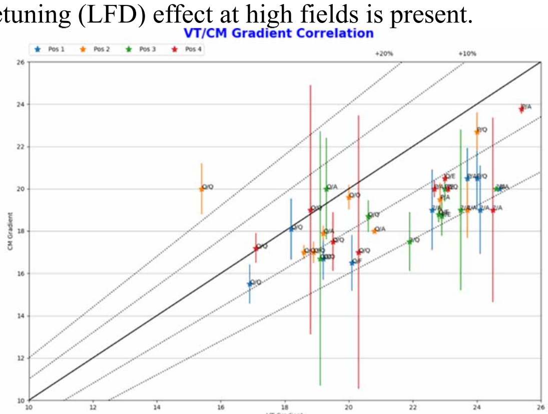

Figure 4: VT/CM Gradient correlation.

Figure 4 shows a correlation plot of the measured limiting gradient for cavities in the CM at TS2 with respect to the vertical tests (VT). With the exception of an outlier (possibly due to a calibration error), all cavities lie on or below the 1:1 correlation curve, within a max 20% deviation. Many of the CM tests are Administratively limited and cannot reach the same condition as the VT, performed in a different RF coupling condition.

For each tested CM a summary report, as shown in Figure 5 is created, with summary of calibrations, measurements and comparison with VT, in order to assist in the RFI decision (e.g. placement in the linac cells).

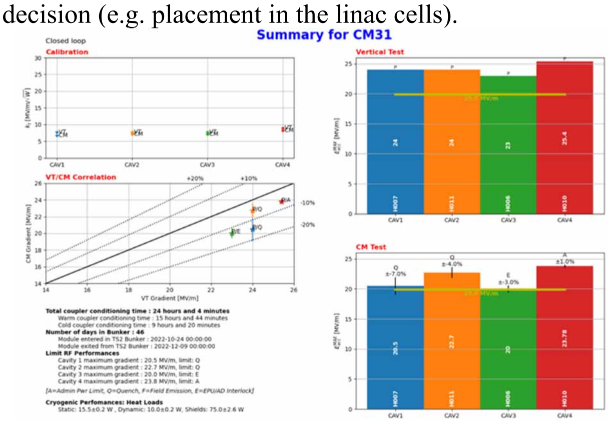

Figure 5: Example test summary report (HB CM31).

Dynamic Heat Loads

An important indicator of cavity performance is the dynamic heat loads (DHL) which indicates the amount of RF power induced from cavity operation and dissipated to the cryogenic system. All tested CMs show a low DHL when compared to the design specification (see Figure 6).

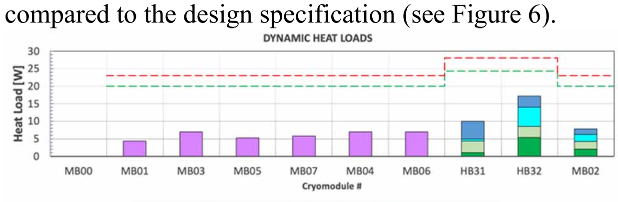

Figure 6: Measured dynamic heat load per CM.

For the last 3 tested CMs we were able to measure the DHL contribution from each cavity at various accelerating gradients. We are introducing this measurement at for all subsequent modules, as an additional gauge for long term cavity performance.

Static Heat Loads

Static heat loads (SHL) to the cryogenic system at 2K are an important indicator of the manufacturing quality of the cryomodule. Some CMs record a SHL slightly above the design estimation but below the design value including margin (see Figure 7).

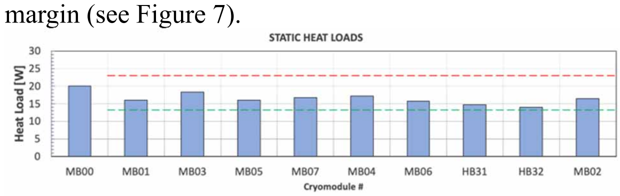

Figure 7: Measured static heat loads per CM.

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Moreover, we note a slight declining trend with each assembled CM, indicating an improvement in manufacturing quality with experience and input from operation.

OPERATION EXPERIENCE

The TS2 operation experience is continuously scrutinized in view of the long testing campaign of series 30 modules, to make use of lessons learned in order to improve testing uncertainties and decrease test times, while allowing for the development and testing of critical subsystems that will be needed during ESS operation.

Downtime Statistics

The continuous operation of TS2 depends on the availability of personnel, equipment, utilities and auxiliary systems. Many factors can affect the optimal SAT plan. Below we list the major causes (planned and unplanned) for deviations to the optimal plan (downtime):

- Non-conformities (investigation and resolution).
- Studies for operation performance improvement.
- Power outages. RF sources trips and interlocks.
- Cryogenics plant trips.
- Network communication fault.
- Water cooling system fault.

Non-Conformities

Non-conformity (NC) is a deviation from the nominal design or reduced performance, always requiring a significant portion of time for further analysis or investigation.

An example of major NCs relate to CM02 beam vacuum and CM32 isolation vacuum, where during inspection or testing, the vacuum pressure levels deviate from nominal, or CM03 where a broken cold cathode vacuum gauge was found. Further analysis is required to assess the root cause of the leak and ways for mitigation and repair when possible. For CM32 a cold leak in the inner cryogenic piping prevents the RFI state, whereas critical beamline components for CM03 and CM02 (a beam vacuum gauge and a coupler antenna) were successfully exchanged at ESS by CEA specialists with the support of ESS/IFJ PAN experts. The data presented in the previous analysis has been taken after these repairs.

Minor type of deviations, also related to vacuum, are encountered during leak check of cryogenics circuits after the CM installation into the bunker. For a few CMs a suspected leak on the inter-connection region was solved by repeating quality controls, cleaning and re-assembly. Even if minor in severity, these types of issues are still time consuming.

Another major NC was detected during the incoming preparation phase where electrical signals are carefully checked. Here a short to ground was present on the helium level gauges assembly. This NC required a design change for all forthcoming CMs and repair of CMs already delivered. Similarly, it was found that one of the CM internal piping had fallen off the supporting hooks during transport.

Minor deviations from design, where some components are missing or wrong materials are used require a meticulous inspection. In most cases requiring an easy replacement, but in few others the replacement can compromise the logical progression of the acceptance phases. An example is the use of wrong material for vacuum seals, which when detected required its replacement but also compromising the already completed leak detection.

Equipment Protection

The high-power couplers of the elliptical cavities have been designed to provide field to the nominal gradients of the cavities. As with all similar couplers, they will fail if presented with fields greatly in excess of the design parameters. In order to prevent damage to the couplers, they are protected by a number of interlocks. The Forward and Reflected Power interlock detects any power in excess of a set number, and allow to comply with the administrative limits discussed before.

Arc detectors placed on both sides of the ceramic window detect arcs in the vacuum or air environment. They are connected via a plastic optical fibre to photomultipliers located in the racks, which provide protection through a fast interlock signal. This is the most common form of trip events we experience during conditioning and operation. The optical fibre is also susceptible to scintillation caused by high levels of radiation, causing spurious trips and potentially masking low-level arcing events.

The electron pick-up unit complements the arc detection and provides a fast and accurate indication of the amount of electron activity in the coupler, but is unlikely to capture any event located elsewhere in the cavity.

Various types of cavity quench detection and cavity (and RF systems) protection interlocks are present, depending on the low level RF (LLRF) mode or operation. Forward and reflected power interlocks can be set to quickly interrupt the RF pulse when the feedback driving the forward power exceeds the expected limits in closed loop. Q_l monitoring allows quench effect mitigation in open loop for pulse to pulse protection. Dedicated interlocks are always active on the circulator and on the klystron systems.

The fast interlock system can be set to detect events during the pulse flat-top and have been shown to be very effective at reducing the disruption in cryogenic operation due to sudden cavity quenches.

The real-time calculation of the Q_l detects deviations caused by drops on the cavity decay, which can be used to react to a slow quench event, developing over several pulses. This is presented in greater detail in a separate paper [7].

CONCLUSION

The TS2 campaign for the ESS CM SAT testing has reached 1/3 of its scope. Test protocols are continuously improved in order to refine the performance characterization and to decrease the testing time, while preparing the subsystems for the technical commissioning of the linac in its first phase at 570 MeV, starting mid 2024.

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REFERENCES

[1] N. Elias *et al.*, "Testing of SRF Cavities and Cryomodules for the European Spallation Source", in *Proc. SRF'17*, Lanzhou, China, Jul. 2017, pp. 95-99. doi:10.18429/JACoW-SRF2017-MOPB018

[2] R. Miyamoto, "Status and Plan of the ESS Proton Linac Beam Commissioning", presented at IPAC'23, Venice, Italy, May 2023, paper WEOGB1, this conference.

[3] M. Jensen, "Overview and Status of ESS RF Systems", presented at IPAC'23, Venice, Italy, May 2023, paper THODB2, this conference.

[4] C. G. Maiano *et al.*, "ESS Elliptical Cryomodules Tests at Lund Test Stand", *in Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 1261-1264. doi:10.18429/JACoW-IPAC2022-TUPOTK026

[5] A. Zwozniak *et al.*, "Radio Frequency System, Power Converters and Cryomodule installation and tests as a Polish In-Kind contribution to the European Spallation Source (ESS)", presented at IPAC'23, Venice, Italy, May 2023, paper MOPL126, this conference.

[6] N. Elias *et al.*, "Heat Loads Measurement Methods for the ESS Elliptical Cryomodules SAT at Lund Test Stand", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2819-2822. doi:10.18429/JACoW-IPAC2022-THPOTK025

[7] M. Wang *et al.*, "RF CM Test Program at ESS TS2", presented at IPAC'23, Venice, Italy, May 2023, paper WEPA151, this conference.